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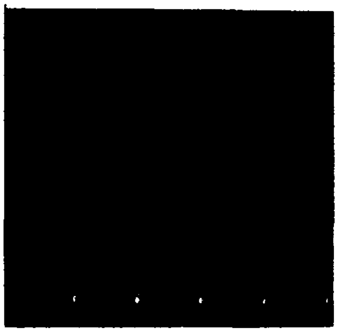

STRUCTURES LABORATORY

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USE OF POZZOLAN OR SLAG IN CONCRETE TO CONTROL ALKALI-SILICA REACTION AND SULFATE ATTACK

by

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Five different materials (one Class C fly ash, two silica fumes, and two ground granulated iron blast-furnace slags (slag) were characterized by a combination of tests, standard physical and physical plus some petrographic examination.

Mortar mixtures were then made using different amounts of each of these materials with high-alkali portland cement. Specimens from these mixtures were tested for expansion due to alkali-silica reaction (ASR) by CRD-C 257 (ASTM C 441) and for expansion due to sulfate attack by CRD-D 211 (ASTM C 1012). The expansion data were evaluated to determine the amount of each material required to control either process or the combined effects of both. A few concrete mixtures were then made using the indicated amounts of the fly ash, silica fume, and slag, and specimens were tested as before to determine the effectiveness of these materials to control deleterious expansion in concrete. Keywords,

In addition, many of the blends of cement with pozzolan or slag that were (Continued)

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19. ABSTRACT (Continued).

used in the mortar mixtures were tested to determine heat of hydration by CRD-C 229 (ASTM C 186). Mortar mixtures were tested for drying-shrinkage in accordance with CRD-C 256 (ASTM C 311).

The results of this work were used to develop a procedure for the evaluation and use of pozzolan (fly ash, silica fume, natural pozzolan) or slag to control the expansive effects of ASR or sulfate attack or both when either or both is considered a potential problem. This procedure is convenient to use and can provide the desired information in as little as 2 or 3 months.

Such an empirical procedure is needed because each combination of a pozzolan or a slag with other materials is a unique situation; therefore, previous data for other such materials are not entirely suitable to determine the amount that is needed for a specific situation.

PREFACE

The work described in this report began in 1984 and was completed in 1987. for the Office, Chief of Engineers, US Army, under Work Unit 32261 of the Civil Works Investigation program for concrete.

All of the work was done in the Concrete Technology Division (CTD) of the Structures Laboratory (SL), of the US Army Engineer Waterways Experiment Station (WES) under the supervision of Mr. John M. Scanlon, Chief, CTD, and Mr. Bryant Mather, Chief, SL. Alan D. Buck, Project Leader, prepared this report, and R. E. Reinhold (retired) was co-Project Leader curing the first part of this project.

John B. Cook of the Cement and Pozzolan Unit, CTD, made and tested most of the mortar specimens for this study.

COL Dwayne G. Lee, CE, is Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
angstroms	0.1	nanometres
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
inches	25.4	millimetres
pounds (force) per square inch	0.006894757	megapascals
Calories per gram	4.184	kilojoules per kilogram

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

USE OF POZZOLAN OR SLAG IN CONCRETE TO CONTROL ALKALI-SILICA REACTION AND SULFATE ATTACK

INTRODUCTION

1. When the environment poses a significant potential for damage to concrete by alkali-silica reaction (ASR) or sulfate attack or both, use of proper amounts of a suitable pozzolan (fly ash, silica fume, natural pozzolan) or a ground granulated iron blast-furnace slag (slag) can prevent such damage. Such use would be especially beneficial for those cases where this would effect an economy.

2. There are two major reasons why this knowledge has not resulted in consistent use of pozzolan or slag to control these damaging chemical reactions. One has been lack of a need due to the ready availability of low-alkali or low-C_3A* portland cement without increased cost; it is anticipated that eventually low-alkali or low-C_3A portland cement will be higher in cost than portland cement not required to meet such limits. Another reason has been that although all materials within a class (i.e., fly ash or silica fume or natural pozzolan or slag) are generally similar they are not interchangeable. For example, the proper amount of one fly ash to use for a specific case is probably not the proper amount for a different combination of materials or a different fly ash. This means that each assemblage of materials (cement, pozzolan or slag, aggregate) for a given project and environment represents a unique situation. Therefore, the selection of the proper amount of a pozzolan or slag to use in any given case will depend on an empirical determination for that case. This lack of interchangeability means that a simple procedure for evaluation and use of a pozzolan or slag to control damaging chemical reaction is needed. This was the basic objective of the present project.

MATERIALS AND METHODS

Mortar

3. A Class C fly ash from Louisiana, silica fumes from Alabama and Kentucky, and a slag from Maryland were initially selected to represent a

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* Usual notation where $C = CaO$, $A = Al_2O_3$, $\bar{S} = \bar{S}O_4$.

geographic distribution where low-C_3A or low-alkali cements might not be readily available. A second slag from the Chicago area was added later. These were single shipments from each source hence material variation from a source over a period of time was not studied. Each material was characterized by a variety of physical, chemical, and petrographic tests.

4. Mortar mixtures were made containing different ratios of fly ash or silica fume or slag to cement by solid volume, mortar bars were molded and exposed to environments that would encourage ASR or sulfate attack, and to determine amounts of pozzolan or slag needed for effective control of expansion.

5. The combinations used for each test method are shown by amount of pozzolan or slag used with each of two cements; most testing was done using one of two shipments of cement RC-756(2) or RC-756(3) with 1.2 to 1.3 percent alkali calculated as Na_2O and 13 to 14 percent calculated C_3A. Less testing was done using cement RC-715 which had 0.9 percent alkali calculated as Na_2O and 11 percent calculated C_3A. Enough monitoring of different shipments of cement RC-756 has been done to conclude that it showed no significant changes from shipment to shipment.

6. ASR(CRD-C257 (ASTM C 441))

a. Fly ash AD-784: The amounts used were 30, 35, 40, 50, 60, and 65 percent by mass of the portland cement. The 40, 60, and 65 percent levels were repeated; one 60 percent mixture included replacement of 1 percent of the aggregate with hydrated lime (CH) by mass. This was done because the concrete mixture made with this fly ash included this amount of CH to increase strength gain. All mortar mixtures were made with cement RC-756(2) or RC-756(3).

b. Silica fume AD-536 (5): 5, 10, and 15 percent (made twice) mixtures were made with cement RC-756(2). One 15 percent mixture was made with cement RC-715.

c. Silica fume AD-797: Same replacement levels and cements used as with fume AD-536(5).

d. Slag AD-798: 30, 35, 40, and 60, and 70 percent mixtures were made with cement RC-756 (2) or RC-756(3); the 40 and 70 percent ones were repeated because the original 40 and 70 percent mixtures were defective.

e. Slag AD-856: 30, 40, 60, and 75 percent mixtures were made with cement RC-756(3).

7. A total of 30 C 441 mortar test mixtures were made. These included some replications to provide expansion data verification or to resolve anomalies and a few to fill in proportioning levels that seemed to be needed.

Four control mixtures without slag or pozzolan were made at four different times with cement RC-756(2) or RC-756(3). One control mixture was made with cement RC-715. Pyrex glass was used as the reactive aggregate for all 35 mixtures.

8. In addition, two mortar mixtures were later made with 60 percent fly ash and a combination of limestone fine aggregate and 3 percent Beltane opal as reactive material instead of Pyrex glass. One mixture contained 1 percent CH by weight of aggregate; the other did not.

9. Sulfate resistance (CRD-C 211 (ASTM C 1012))

a. Fly ash AD-784: 50 and 65 percent mixtures were made with cement RC-756(2). The 65 percent mixture was repeated using CH for 1 percent of the aggregate by mass.

b. Silica fume AD-536(5): 10 and 15 percent mixtures were made with cement RC-756(2). The 10 percent one was made again with a different water to cementitious solids (w/s) ratio.

c. Silica fume AD-797: 10 and 15 percent mixtures were made with cement RC-756(2).

d. Slag AD-798: 40, 50, 60, and 75 percent mixtures were made with cement RC-756(2) or RC-756(3); the 50 percent one was repeated.

e. Slag AD-856: 30, 40, 60, and 75 percent mixtures were made with cement RC-756(3); the 40 percent mixture was repeated.

10. A total of 18 test mixtures were cast to evaluate sulfate resistance. This included one additional fly ash mixture with CH, three additional mixtures with slag AD-798, and one with slag AD-856 to resolve anomalies and to provide additional expansion data. One control mixture was made with cement RC-756(3). In addition, expansion data for an earlier control mixture made with the original shipment of cement RC-756 with bars stored in sodium sulfate solution, instead of the mixed sodium and magnesium sulfate solution, were also used for comparison. Standard siliceous sand was used for all 19 (18 test, 1 control) mixtures.

11. Heat of hydration (CRD-C 229 (ASTM C 186)). The effect of blending different amounts of each of the five materials with high-alkali cement RC-756(3) on the heat of hydration was determined. Additional work was done with blends of slag AD-798 and cement RC-756(3) to determine whether it is necessary to use a corrected value for loss on ignition for slag. The combinations of each material used with cement RC-756(3) for heat of hydration data were:

Fly ash AD-784. 30, 40, and 60 percent.

Silica Fume AD-536(5). 5, 10, and 15 percent.

Silica Fume AD-797. Same as above.

Slag AD-798. 30, 40, and 70 percent.

Slag AD-856. Same as above.

12. Drying-shrinkage (CRD-C 25 (ASTM C 157), CRD-C 256 (ASTM C 311)). In general, the same pozzolan or slag and cement mortar blends as those tested for ASR were made and tested for drying shrinkage using cement RC-756(2) or RC-756(3). This was repeated with cement RC-715 except that slag AD-856 was not used.

Concrete

13. Air-entrained concrete mixtures were made to evaluate the effect of using the amount of pozzolan or slag in concrete that was indicated as needed by testing of mortar. Control mixtures contained limestone coarse aggregate (CL-2 MG-4) with all material retained on a 19.0-mm (3/4-in.) sieve removed, a standard laboratory siliceous sand, and high-alkali and high-C_3A cement RC-756(3). Test mixtures, in addition to the above materials, also contained a specified amount of pozzolan or slag for the cement and 3 percent of the siliceous fine aggregate was replaced with reactive Beltane opal (CL-4 G-1) as 1 percent by mass in three sieve sizes; these were:

Passing 2.36-mm (No.8), retained 1.18-mm (No. 16 sieve)

Passing 1.18-mm, (No. 16), retained 600-μm (No. 30 sieve)

Passing 600-μm (No. 30), retained 300-μm (No. 50 sieve)

This amount of opal, 3 percent, is the pessimum for this cement (Buck and Mather, 1987). The water to cementitious solids ratio (w/s) was 0.58 for the first slag (AD-798) test mixture, the w/s was required to be not more than 0.55 for the other test mixtures. The w/c was 0.55 for all control mixtures. Air content and slump were measured for each batch of concrete immediately after mixing. The main control parameter, in addition to w/c or w/s, was that the concrete reach a compressive strength of 20.7 MPa (3,000 psi) in a reasonable time since it had been decided that the sulfate resistance test should not start until this level of maturity was reached.

14. Specimens cast from each control and test mixture included 50.8- by 50.8- by 254-mm (2- by 2- by 10-in.) bars for expansion testing and 76.2- by 152.4- or 101.6 by 203.2-mm (3- by 6-in. or 4- by 8-in.) cylinders for compressive strength determinations. The sulfate resistance method used was based, in principle, on ASTM C 1012 using a mixed sulfate solution.

RESULTS

Mortars

15. Materials. The fly ash was tan, the fumes were light gray (AD-536(5)) and darker gray (AD-797), and the slags were pale gray in color. Table 1 shows a comparison of selected chemical and physical properties. Major differences in the fumes were higher SiO_2 content and fineness for AD-536(5). The two slags differed mainly in that AD-798 was ground finer than AD-856. Limited petrographic and X-ray diffraction (XRD) examination showed the fumes and the slags to be largely glassy. Fume AD-536(5) showed no detectable crystalline material. Fume AD-797 showed a small amount of what was probably magnetite; this is consistent with its much higher iron content (Table 1). Slag AD-798 was estimated to be more that 90 percent glassy by inspection of an immersion mount with a polarizing microscope; XRD indicated a little crystalline material that was probably the calcium magnesium silicate, merwinite. Slag AD-856 was similar but probably contained more crystalline material. XRD indicated the presence of merwinite and the calcium magnesium aluminosilicate, melilite, both are common slag phases, and quartz; a small amount of calcite was seen in an immersion mount. The amorphous hump seen by XRD was at about 0.4-nm for the fumes and about 0.3-nm for the slags; this difference relates to differing composition of the glass in the fumes and the slags.

16. Table 1A shows chemical and physical data for three shipments of high-alkali cement RC-756. These data show the uniformity of the cement in these shipments. Complete analyses for RC-756 and RC-756(2) were published in a report by Reinhold, Richter, Buck, Mather, Mather, and McDonald (1986). Since an analysis for the less used high-alkali cement RC-715 was also included in that report, it is not repeated here.

17. The fly ash, while glassy, contained much less glass than the fumes and slags. Several crystalline phases were indicated by XRD. In addition to quartz, mullite, hematite, and magnetite which are common to most fly ashes, anhydrite ($C\bar{S}$), CaO, MgO, $C_4A_3\bar{S}$, and possibly an aluminoferrite and C_3A were tentatively identified; the latter six phases are typical of those sometimes found in Class C fly ash such as AD-784. XRD showed the amorphous hump for the fly ash glass to be at about 0.3-nm; this is about 28 1/2°2θ for copper radiation. Diamond (1983) says a hump in this area indicates a siliceous

rather than a calcium aluminate glass. Extrapolation of his curve for amount of analyzed CaO versus the position of the amorphous hump gave a value of about 23 percent CaO for this ash; this is what was calculated from chemical analysis (Table 1). Although this was a high lime ash, the amount of crystalline lime (CaO) by XRD, as indicated earlier, did not seem high.

18. When a small amount of the fly ash was mixed with water, the mixture hardened within 30 min. A sample of the hardened material was kept continuously immersed in water for about 14 months and then examined by XRD. A fast pattern of a sawed and ground surface showed only residual quartz and hematite of the original crystalline phases plus a weak new 1.2-nm peak. A slow pattern of material ground to pass a 45-μm (No. 325) sieve differed largely from the fast pattern by showing substantial amounts of ettringite that have not been seen before. It is believed that the 1.2-nm phase was CSH-I. The slow pattern showed that the original MgO was essentially unaffected by hydration.

19. Since some of the ash was used over a period of at least 2 years there was some concern that it might have been altered by hydration of the CaO during this storage period. Examination of different portions of the stored material by XRD indicated that no changes had occurred.

20. Alkali-Silica Reaction (ASR). Some of the expansions that were obtained by using different amounts of the three types of materials (fly ash, silica fume, slag) and testing as mortars by ASTM C 441 are shown in Tables 2 and 2A (fly ash), 3 (silica fume AD-536(5)), 4 (silica fume AD-797), 5 (slag AD-798), and 6 (slag AD-856). Table 6A shows the reproducible results that were obtained using different shipments of RC-756(2) or RC-756(3) in four control mortar mixtures (i.e., no pozzolan or slag) over about a 2-year period. Expansion data for one control mixture with high-alkali cement RC-715 were similar.

21. An expansion criterion of less than 0.10 percent up to 1 year of testing with no expectation that it would exceed this value if testing continued was used to evaluate expansions due to ASR. Application of this criterion suggests that:

a. The data in Table 2 indicate that 60 percent of this ash was the amount to use to satisfactorily control expansion. The data also show increased expansion at the 65 percent level. This could suggest a pessimum effect or enough range in expansion data to mask a general decrease in expansion with

increasing amount. Since a small amount of CH was used in a concrete mixture with 60 percent of this fly ash to accelerate strength gain, a few mortar mixtures with 60 percent ash were made to evaluate its effect on expansion. These data are shown in Table 2A. The use of CH increased the expansion of specimens made using the mortar mixture containing Pyrex glass as aggregate but had no effect on a mixture made with siliceous fine aggregate and three percent reactive Beltane opal. The pH of the two mortar mixtures with Pyrex glass was determined at an early age to see if the presence of CH caused a significant difference; it did not.

b. For cement RC-756(2), 5 percent of either silica fume was not enough, but 10 or 15 percent of either was enough (Tables 3, 4). The same tests were made using the other cement, RC-715, with and without 15 percent of each fume. Expansion data were similar to those shown in Tables 3 and 4 for these same conditions.

c. At least 60 percent of either slag was required (Tables 5, 6) for cement RC-756(2) or RC-756(3).

22. Sulfate Resistance. Some of the expansions that were obtained by using different amounts of the three types of materials and testing as mortars by ASTM C 1012 are shown in Tables 7 (fly ash), 8 (silica fume AD-536(5)), 9 (silica fume AD-797), 10 (slag AD-798), and 11 (slag AD-856). Evaluations were based on keeping expansion below 0.10 percent at 1 year as before. Inspection of the data in Tables 7 through 11 suggest:

a. Both 50 and 65 percent levels of this fly ash with RC-756(2) and RC-756(3) were enough (Table 7); lower values were not tested for sulfate resistance. The two control mixtures made without ash with one stored in sodium sulfate solution and one stored in a mixed solution of sodium and magnesium sulfate show slower expansion in the latter solution as expected. Use of CH for 1 percent of the sand with the 65 percent ash mixture did not affect expansion.

b. Table 8 shows that either 10 or 15 percent of silica fume AD-536(5) was enough with cement RC-756(2).

c. Table 9 shows that 10 percent of silica fume AD-797 was not enough while 15 percent was enough with cement RC-756 (2).

d. The 1984 expansion data shown in Table 10 for 50 and 75 percent slag AD-798 indicated that 75 percent slag would be needed to control expansion due to sulfate attack. A repeat of the 50 percent slag mixture and additional mixtures with 40 and 60 percent of this slag were made in 1986. None of these three mixtures showed any significant expansion through 1 year of testing. The original 50 and 75 percent mixtures consisted of only two and three bars, respectively, while the later three mixtures were each represented by six bars. At this point the original expansion data for the 50 percent mixture appear to be

incorrect for some unidentified reason. In general, the data in Table 10 indicate that 40 percent of slag AD-798 would be enough to control expansion due to sulfate attack, but 60 percent was needed to control ASR (Table 5).

e. While none of the 4 mixtures with cement RC-756(3) and 30 to 75 percent of slag AD-856 show too much expansion after 365 days of testing (Table 11), the ASR data (Table 6) do suggest that at least 60 percent slag would be needed.

23. Heat of hydration. These values are shown in Table 12. The values as kJ/kg generally show decreases with increasing amounts of fly ash and the two slags at both 7- and 28-day ages. However, this trend was not repeated for the low amounts (5, 10, 15 percent) of either silica fume that were used. Instead there was little or no change and some reversals.

24. Drying-shrinkage. These data for mortar mixtures at 28 and 180-day ages are shown in Table 13 for cement RC-756(2) or RC-756(3) and Table 14 for the lower alkali cement RC-715. This work was done to determine if the amounts of pozzolan or slag found necessary to control expansion due to a deleterious chemical reaction or reactions would result in a detrimental amount of drying shrinkage. While the data tend to show decreasing shrinkage for increasing amounts of fly ash or slag and increasing shrinkage for more fume, the values seem to indicate that the effect of drying shrinkage would not be significant, especially for the lower shrinkage values that would be associated with concrete rather than mortar. The values of about 0.2 percent for 20 percent of either fume might be an exception, but indications are that 20 percent fume would not be needed to control expansion due to chemical reaction.

Concrete

25. The control mixtures contained high-alkali and high-C_3A cement RC-756(3) without reactive aggregate (opal). The intent was for them to be affected by sulfate attack but not by ASR. Each test mixture had the ingredients to cause sulfate attack and ASR, in the proper environment, plus the amount of pozzolan or slag believed to be needed to resist such attacks. Expansion data for moist storage at room temperature, for ASR, and for sulfate resistance plus compressive strength data are shown in Tables 15 through 22. They are discussed individually in the following paragraphs.

26. Concrete test mixture with 75 percent slag AD-798 and a control mixture. Expansion data are shown in Table 15; compressive strength data are shown in Table 16. The control mixture CL-57 CON(R) showed excessive

expansion by 1 year due to sulfate attack as expected. The use of this amount of slag was effective in preventing significant expansion due to ASR or sulfate attack. However, as later mortar bar data became available (Tables 5 and 10), it became apparent that 60 percent of this slag would have been enough to use. Although control mixture cylinders reached the selected 20.7 MPa (3,000 psi) based on ASTM C 1012 in 2 days the test mixture specimens required 12 days. Therefore, 60 percent of this slag and a water to cementitious solids ratio of 0.55 instead of the 0.58 that was used would have been preferable in order to reach the specified strength level sooner. Since there was no ASR with this or subsequent repeats of the control mixture because there was no reactive aggregate (opal) in it, a control mixture with the pessimum amount of reactive opal (3 percent) was cast in late 1986 and concrete specimens were tested by ASTM C 441; expansion data for it are also shown in Table 15; expansion was significant.

27. Concrete test mixtures with 10 percent silica fume AD-536(5), 15 percent silica fume AD-797, and a control mixture. More of silica fume AD-797 was used because expansion data for mortar in Table 9 indicated that 10 percent was not enough to control expansion due to sulfate attack. The expansion data in Table 17 show that the amounts of silica fume used were adequate to control expansion due to ASR and or sulfate attack. Compressive strength data are in Table 18; the rate of strength gain was not retarded by the use of either amount of silica fume.

28. Concrete test mixtures with 60 percent fly ash AD-784, 60 percent slag AD-856, and a control mixture. Expansion data are shown in Table 19, and there was no deleterious expansion for either test mixture. Compressive strength data are shown in Table 20. The time to reach 20.7 MPa (3,000 psi) was not excessive for either test mixture. There were significant difficulties in obtaining the desired strength level of 20.7 MPa (3,000 psi) in a reasonable time for the fly ash mixture. Among the things that were tried were increasing the cement content, using warm mixing water, and use of a non chloride based accelerator. None of these were effective for this mixture. Since it was known from associated work with mortar using this cement and this fly ash that replacement of 1 percent of the fine aggregate with fine slaked lime (CH) by mass did accelerate strength gain, this was done for this concrete mixture. Additional testing of mortar containing this cement, 60 and 65 percent of this ash, and replacement of 1 percent fine aggregate by CH was done

and expansion data are shown in Tables 2A and 7. However, none of the excessive expansion effect due to ASR for mortar was reflected in the concrete data.

29. Expansion data due to sulfate attack for the 3 rounds of the control mixture are given in Tables 15, 17, and 19 and combined in Table 21. The compressive strength data from Tables 16, 18, and 20 for the control mixture were put together in Table 22. It is likely that the decreasing expansion of subsequent rounds of this mixture were due to the increasing strength of the concretes by round. If expansion testing had been continued, the deleterious effect of sulfate attack would probably be seen.

30. Compressive strength data for the later rounds of the control mixture with reactive opal are also shown in Table 22. These strength values were consistent with previous ones.

DISCUSSIONS

31. It is known that differences between classes of materials (fly ash, silica fume, slag, natural pozzolan) and within each class of material may mean that different amounts may be needed to control expansion due to ASR or sulfate attack for each case. Such differences in the needed amounts of the two fumes and the two slags from different sources were indicated. It is also known that subsequent supplies of material from a single source can be different. If a coal-burning power plant changes its source of coal or changes its combustion procedures, the fly ash characteristics may also change. The need is to know the actual amount of a particular fly ash or silica fume or slag or natural pozzolan that is needed to control deleterious expansion for a specific combination of concrete constituents using a specific cement. With these considerations and this need in mind the following procedures are suggested as a means for achieving this.

For a potential ASR problem:

a. The proposed material should be given a preliminary characterization by a combination of physical, chemical, and petrographic methods to assure that it is a reasonable candidate material and that it meets the applicable CE or ASTM specifications.

b. Prepare four mortar mixtures according to CRD-C 257 (ASTM C 441). Use the proposed cement or a high-alkali cement and Pyrex glass as the aggregate on the assumption that if the candidate pozzolan (fly ash, silica fume, or natural pozzolan)

or slag will control this combination it will control the actual job materials. Pyrex glass is preferred since its pessimum amount is 100 percent. This avoids the need to conduct tests to determine the pessimum amount of reactive material in the actual aggregate and possible fluctuations in test results due to non-uniformity of the aggregate. A control mixture without pozzolan or slag should be made. Use the level of pozzolan or slag expected to obtain adequate control for the second mixture, this amount will probably be 20 to 60 percent for a fly ash, 10 to 15 percent for a silica fume, 20 to 30 percent for a natural pozzolan, and 50 to 75 percent for a slag. Use about 10 to 15 percent more and 10 to 15 percent less for the third and fourth mixtures.

c. Test the bars from these mixtures by CRD-C 257 (ASTM C 441) for a minimum of 14 days, longer if possible.

d. Evaluate the expansion data to determine the amount of the slag or pozzolan needed to keep expansion levels from exceeding 0.10 percent at 1 year. All mortar bars that showed 0.10 percent or less expansion at 1 year in these tests had 0.06 percent or less expansion at 14 days.

e. This is the amount to use in the concrete. It may be necessary to make slight modifications to the intended concrete mixture to assure desired workability or strength gain or other needed properties.

f. Once a material and its amount to use has been selected, the continued suitability of this material during the duration of construction should be periodically monitored by selected physical or chemical or petrographic methods or a combination of these. For example, one might use fineness, silica content, or relative amount of glass. Similar monitoring should be used for the cement. The frequency of testing and parameters to be used must be determined by the user.

g. It is desirable to approximate the actual environmental conditions during the laboratory testing. If there is a significant source of alkali from the environment, it may affect the control provided by the pozzolan or slag and could necessitate the use of non-reactive aggregate.

For a potential sulfate attack problem:

a. Follow a similar strategy, omitting the reactive aggregate, using CRD-C 211 (ASTM C 1012) as the test method to determine the amount of material needed to keep expansion well below 0.10 percent. It is desirable to run the test for 1 year.

For combined ASR and sulfate attack:

b. Use both procedures and select the highest replacement level of pozzolan or slag indicated by the results.

32. In general, it is preferable to use either or both of these procedures rather than to try to predict an amount of material to use without any

performance data since each situation and combination of materials is unlike any other. The time required to determine an amount to use may be as short as a few months or as long as a year. Aspects of these procedures were described previously (Buck, 1985; Buck and Mather, 1987).

33. It should be recognized that use of 50 or more percent of a fly ash or a slag in a concrete mixture will result in a considerably slower strength gain unless reasonable steps are taken to avoid it. The need for such steps should be considered.

CONCLUSION

34. The use of different amounts of fly ash, silica fume, and slag to control expansions due to ASR or to sulfate attack or both in mortars and concretes was evaluated. As a result, empirical strategies were devised to determine the amount of a specific material to use to control either or both of these reactions for actual construction. Once this has been done, the uniformity of the selected material and the cement should be monitored during construction.

35. Tests using mortar mixtures indicated no significant undesirable effects on either heat of hydration or drying shrinkage of using the amounts of these pozzolans or slags that were found to be needed to control expansion due to undesirable chemical reaction or reactions.

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Table 1

Selected Chemical and Physical Data for Five Materials

	Fly ash	Silica Fume		Slag	
Chemical, %	AD-784	AD-536(5)	AD-797	AD-798	AD-856
SiO_2	-	96	80	36	35
Al_2O_3	-	1	2	10	8
Fe_2O_3	-	1	6	1	<1
$SiO_2 + Al_2O_3 + Fe_2O_3$	63				
MgO	5	<1	1	9	11
Sulfide Sulfur	-	-	-	1	1
SO_3	2	<1	2	trace	trace
Alkali as Na_2O	n.d.[a]	0.6	1.4	0.4	0.5
CaO	23	<1	1	42	40
Physical					
Retained on 45-μm (No. 325) sieve	6	1	n.d.	1	1
Fineness, m^2/kg	n.d.	12,800[b]	8750[b]	535	415
Density (S.G.) Mg/m^3	2.7	2.2	2.2	2.9	2.9
Lime-Pozzolan strength, MPa (psi)	10.7 (1550)	14.8 (2,140)	10.5 (1530)	-	-
Slag Activity Index, 28-day	-	-	-	128	120
Hydraulic Activity with Alkali[c]	-	-	-	14.5 MPa	15.1 MPa

(a) Not determined.

(b) Extrapolated to e = 0.500

(c) ASTM E 1085

Table 1A

Selected Chemical and Physical Data for Three Shipments of High-Alkali Cement RC-756

Chemical Data	RC-756[a]	RC-756(2)[a]	RC-756(3)
SiO_2, %	19.9	19.9	19.2
Al_2O_3, %	6.9	6.2	6.7
Fe_2O_3, %	2.2	2.1	2.1
CaO, %	62.9	62.9	62.8
MgO, %	3.0	2.7	2.8
SO_3, %	2.9	3.0	3.0
Loss on Ignition, %	0.7	1.0	1.0
Insoluble Residue, %	0.30	0.17	0.23
Na_2O, %	0.32	0.28	0.27
K_2O, %	1.27	1.57	1.40
Alkalies-Total as Na_2O, %	1.16	1.31	1.19
Alkalies-Water Soluble as Na_2O	0.86	(b)	(b)
Physical Data			
C_3S, %	48	52	53
C_3A, %	15	13	14
C_2S, %	21	18	15
$C_3A + C_3S$, %	62	65	67
C_4AF, %	7	6	6
$C_4AF + 2C_3A$, %	(b)	(b)	35
Surface Area, m^2/kg	403	377	421
Air Content, %	9	9	9
Comp. Strength, 3D, MPa (psi)	24.2 (3,510)	25.5 (3,700)	25.9 (,3750)
Comp. Strength, 7D, MPa (psi)	27.9 (4,050)	30.9 (4,480)	32.0 (4,640)
Comp. Strength 28D, MPa (psi)	32.3 (4,690)	35.4 (5,130)	(b)
Autoclave Exp., %	0.10	0.09	0.11
Initial Set, Hr/min	2:45	2:35	3.40
Final Set, Hr/min	5:15	4:55	5:55

(a) Complete analyses for these two cements are in Reinhold, Richter, Buck, Mather, Mather, and McDonald (1986).

(b) Not determined.

Table 2

Alkali-Silica Reaction Expansion of Mortar Bars[a] with Fly Ash AD-784 and High-Alkali Cement RC-756(2) or RC-756(3)

Age, Days	Average Expansion, %								
	No Ash[b]	30% Ash[b]	35% Ash[b]	40% Ash		50% Ash[c]	60% Ash[b]	65% Ash	
14	0.43	0.10	0.07	0.15[b]	0.12[c]	0.11	0.03[b]	0.13[c]	0.13[c]
28	0.47	0.12	0.09	-	0.13	0.12	0.04	-	0.15[d]
56	0.53	0.14	0.09	0.18	0.14[d]	0.12[d]	0.04	0.14	
90	0.50	0.14	0.09	0.18			0.04	0.14	
180	0.51	0.14	0.10	0.19			0.04	0.14	
270	0.51	0.15	0.10	0.19			0.05	0.15	
365	0.51	0.15	0.10	0.20			0.05	0.15	

(a) Tested in accordance with ASTM C 441.

(b) Six mixtures cast mid 1984.

(c) Three mixtures cast early 1986.

(d) Stopped test.

Table 2A

Effect of Hydrated Lime (CH) on ASR Expansion of Mortar Bars[(a)] Made with High-Alkali Cement RC-756[(3)] and 60% Fly Ash AD-784

Age, Days	Pyrex glass as Aggregate: No CH (b)	Pyrex glass as Aggregate: 1% CH Replacing Aggregate[(c)]	Siliceous Sand Aggregate with 3% Replacement by Beltane opal: No CH[(d)]	Siliceous Sand Aggregate with 3% Replacement by Beltane opal: 1% CH for Sand[(d)]
	Average Expansion, %			
14	0.03	--	0.02	0.01
28	0.04	0.13	0.03	0.02
56	0.04	0.14	0.04	0.02
90	0.04	(e)	0.05	0.03
180	0.04		0.05	0.04
365	0.05		(e)	(e)

(a) Tested in accordance with ASTM C 441.

(b) Repeated from Table 2 for 1984 mixture.

(c) Mixture made mid 1986.

(d) Two mixtures cast Fall 1986.

(e) Stopped test.

Table 3

Alkali-Silica Reaction Expansion of Mortar Bars[a] Made with Different Amounts of Silica Fume AD-536(5) and High-Alkali Cement RC-756(2)

	Average Expansion, %[b]			
Age, Days	No Fume	5% Fume	10% Fume	15%[c] Fume
14	0.43	0.08	0.02	0.01
28	0.47	0.11	0.03	0.01
56	0.53	0.13	0.04	0.02
90	0.50	0.14	0.05	0.03
180	0.51	0.14	0.05	0.03
270	0.51	0.15	0.06	0.04
365	0.51	0.15	0.06	0.04

(a) Tested in accordance with ASTM C 441.

(b) Five mixtures cast mid 1984.

(c) Average values for two castings.

Table 4

Alkali-Silica Reaction Expansion of Mortar Bars[a] Made with Silica Fume AD-797 and High-Alkali Cement RC-756(2)

	Average Expansion, %[b]			
Age, Days	No Fume	5% Fume	10% Fume	15%[c] Fume
14	0.43	0.12	0.01	0.01
28	0.47	0.16	0.03	0.01
56	0.53	0.19	0.04	0.03
90	0.50	0.19	0.04	0.03
180	0.51	0.20	0.04	0.04
270	0.51	0.20	0.05	0.04
365	0.51	0.21	0.05	0.04

(a) Tested in accordance with ASTM C 441.

(b) Five mixtures cast mid 1984.

(c) Average values for two castings.

Table 5

Alkali-Silica Reaction Expansion of Mortar Bars[(a)] Made with Different Amounts of Slag AD-798 and High-Alkali Cement RC-756(2) or RC-756(3)

	Average Expansion, %					
Age, Days	No Slag[(b)]	30% Slag[(b)]	35% Slag[(b)]	40% Slag[(c)]	60% Slag[(b)]	70% Slag[(c)]
14	0.43	0.08	0.05	0.06	0.03	0.01
28	0.47	0.11	0.18	0.07	0.04	0.01
56	0.53	0.12	0.19	0.08	0.04	0.02
90	0.50	0.13	0.19	0.09	0.04	0.02
180	0.51	0.13	0.19	0.08[(d)]	0.04	0.02[(d)]
270	0.51	0.14	0.20		0.05	
365	0.51	0.14	0.20		0.05	

(a) Tested in accordance with ASTM C 441.

(b) Four mixtures cast mid 1984.

(c) Two mixtures cast mid 1985.

(d) Bars discarded accidentally.

Table 6

Alkali-Silica Reaction Expansion of Mortar Bars[a] Made with Different Amounts of Slag AD-856 and High-Alkali Cement RC-756(3)

Age, Days	Average Expansion, %[b]				
	No Slag	30% Slag	40% Slag	60% Slag	75% Slag
14	0.39	0.14	0.07	0.01	0.01
28	0.47	0.15	0.09	0.02	0.01
56	0.51	0.17	0.10	0.02	0.01
90	0.51	0.17	0.11	0.02	0.01
180	0.51	0.17	0.11	0.03	0.02
270	0.51[c]	0.16[d]	0.11[d]	0.03[d]	0.02[d]

(a) Tested in accordance with ASTM C 441.

(b) Five mixtures cast mid 1985.

(c) Stopped test.

(d) Bars discarded accidentally.

Table 6A

ASR Expansion of Mortar Bars Made with High-Alkali Cement RC-756(2) or RC-756(3) and Pyrex Glass

Age, Days	Cast July 1984	Cast May 1985	Cast July 1985	Cast March 1986	All Mixtures
			Average Expansion, %		
14	0.43	0.39	0.40	0.36	0.40
28	0.47	0.47	0.50	0.51 (b)	0.49
56	0.50	0.51	0.53		0.51
90	0.50	0.51	0.54		0.52
180	0.50	0.51	0.54 (b)		0.52
270	0.51	0.51 (b)			0.51
365	0.51				0.51

(a) Made and tested in conformance with ASTM C 441.

(b) Stopped test.

Table 7

Sulfate Resistance of Mortar Bars[a] Made with Different Amounts of Fly Ash AD-784 and High C_3A Cement RC-756

Age, Days	No Ash[b]		50% Ash[c]	65% Ash[c]	65% Ash and 1% CH[d]
	Average Expansion, %				
7	0.00	0.02	0.00	0.00	0.00
21	0.02	0.02	0.01	0.01	0.01
28	0.02	0.02	0.01	0.01	0.01
56	0.10	0.03	0.02	0.02	0.02
90	0.61[e]	0.04	0.02	0.03	0.03
180		0.09	0.04	0.04	0.04
270		0.22[e]	--	--	--
365			0.06	0.05	0.05

(a) Tested in accordance with ASTM C 1012.

(b) *Data on left for RC-756 in Na_2SO_4 solution;* data on right for RC-756(3) in mixed solution; latter cast mid 1985.

(c) Two mixtures cast mid 1984 using RC-756(2).

(d) CH used to replace 1 percent of the sand; cast early 1986 using RC-756(3).

(e) Test stopped.

Table 8

Sulfate Resistance Test of Mortar Bars[a] Made with Different Amounts of Silica Fume AD-536(5) and High C_3A Cement RC-756

	Average Expansion, %[b]			
Age, Days	No Fume	10% Fume[d]	10% Fume[c]	15% Fume[c]
7	0.02	0.00	0.01	0.00
21	0.02	0.01	0.01	0.01
28	0.02	0.01	0.02	0.01
56	0.03	0.02	0.02	0.02
90	0.04	0.02	0.02	0.02
180	0.09	0.03	0.03	0.04
270	0.22[e]	--	--	--
365		0.05	0.04	0.05

(a) Tested in accordance with ASTM C 1012.

(b) Control mixture cast mid 1985 with RC-756(3); three test mixtures cast Fall 1984 with RC-756(2).

(c) Made with 0.422 w/s.

(d) Made with 0.546 w/s.

(e) Test stopped.

Table 9

Sulfate Resistance of Mortar Bars[a] Made with Different Amounts of Silica Fume AD-797 and High C_3A Cement RC-756

Age, Days	Average Expansion, %[b] No Fume	10% Fume	15% Fume
7	0.02	0.01	0.01
21	0.02	0.01	0.01
28	0.02	0.01	0.02
56	0.03	0.02	0.02
90	0.04	0.03	0.03
180	0.09	0.03	0.03
270	0.22[c]	--	--
365		0.10	0.08

(a) Tested in accordance with ASTM C 1012.

(b) Control mixture cast mid 1985 with RC-756(3); two test mixtures cast Fall 1984 with RC-756(2).

(c) Test stopped.

Table 10

Sulfate Resistance Test of Mortar Bars[a] Made with Different Amounts of Slag AD-798 and High C_3A Cement RC-756

	Average Expansion, %					
	Amount of Slag					
Age, Days	None[b]	40[d]	50[d]	50[c]	60[d]	75[c]
7	0.02	0.00	0.01	0.01	0.00	0.01
21	0.02	0.02	0.02	0.01	0.01	0.02
28	0.02	0.02	0.02	0.02	0.01	0.02
56	0.03	0.02	0.02	0.02	0.02	0.02
90	0.04	0.03	0.03	0.03	0.02	0.03
180	0.09	0.04	0.03	0.04	0.03	0.04
270	0.22[e]	0.04	0.04	0.13	0.03	0.05
365	--	0.04	0.04	0.46	0.03	0.05

(a) Tested in accordance with ASTM C-1012.

(b) Control mixture cast mid 1985 with RC-756(3).

(c) Two mixtures cast Fall 1984 with RC-756(2).

(d) Three mixtures cast early 1986 with RC-756(3).

Table 11

Sulfate Resistance Test of Mortar Bars[a] Made with Different Amounts of Slag AD-856 and High C_3A Cement RC-756 (3)

	Average Expansion, % Amount of Slag					
Age, Days	None[b]	30%[b]	40%[b]		60%[b]	75%[b]
7	0.02	0.00	0.02	0.01[c]	0.01	0.01
14	0.02	0.01	0.02	0.01	0.01	0.01
21	0.02	0.02	0.03	0.02	0.02	0.01
28	0.02	0.02	0.03	0.02	0.02	0.02
56	0.03	0.02	0.03	0.03	0.02	0.02
90	0.04	0.03	0.04	--	0.02	0.02
180	0.09	0.04	0.04	0.03	0.03	0.02
270	0.22[d]	0.04	0.05	0.03	0.03	0.02
365		0.06	0.06	0.04	0.04	0.03

(a) Tested in accordance with ASTM C-1012.

(b) Five mixtures cast mid 1985.

(c) Forty percent mixture repeated early 1986.

(d) Test stopped.

Table 12

Heat of Hydration Data[a] for Different Amounts of Five Materials with Cement RC-756(3)

Material	Replacement Level by Solid Volume, %	Heat of Hydration, kJ/kg 7 days	Heat of Hydration, kJ/kg 28 days	Reduction in Heat of Hydration, % 7 days	Reduction in Heat of Hydration, % 28 days
RC-756(3) cement	Zero	356	388	--	--
AD-784	30	301	335	15	14
Class C	40	276	305	22	22
Fly ash	60	247	268	31	31
AD-536(5)	5	331	360	7	8
Silica fume	10	339	364	5	6
	15	322	347	9	11
AD-797	5	335	368	6	5
Silica fume	10	335	364	6	6
	15	331	360	7	8
AD-798	30	326	372	8	4
Slag	40	322	360	9	8
	70	264	305	26	22
AD-856	30	331	364	7	6
Slag	40	322	360	9	8
	70	251	297	29	24

(a) Determined in accordance with ASTM C 186.

Table 13

Drying-Shrinkage Data for High-Alkali Cement RC-756(2) or RC-756(3) with Different Amounts of Pozzolan or Slag at 28 and 180-Day Ages[a]

	Drying-Shrinkage (%) At			
	28 Days		180 Days	
	Within a Mixture	Between Test and Control Mixtures	Within a Mixture	Between Control and Test Mixtures
RC-756(2)	S_c 0.147		S_c 0.150	
	S_t	S_t-S_c	S_t	S_t-S_c
With Fly Ash AD-784				
20%[b]	0.167	0.02	0.176	0.03
35%	0.136	-0.01	0.137	-0.01
40%	0.127	-0.02	0.126	-0.02
60%	0.091	-0.06	0.094	-0.06
65%	0.065	-0.08	0.083	-0.07
With Silica Fume AD-536(5)				
5%	0.147	0.00	0.152	0.00
10%	0.162	0.02	0.170	0.02
15%	0.178	0.03	0.198	0.05
20%[b]	0.192	0.04	0.230	0.08
With Silica Fume AD-797				
5%	Missed	--	0.167	0.02
10%	0.123	-0.02	0.183	0.03
15%	0.143	0.00	0.210	0.06
20%[b]	0.209	0.06	0.242	0.09
With Slag AD-798				
20%[b]	0.137	-0.02	0.153	0.00
30%	0.122	-0.02	0.152	0.00
35%	0.119	-0.03	0.153	0.00
40%	0.106	-0.04	0.136	-0.01
60%	0.109	-0.04	0.143	-0.01
70%	0.119	-0.03	0.163	0.01
RC-756(3)	S_c 0.104		S_c 0.130	
	S_t		S_t	
With Slag AD-856				
20%[b]	0.082	-0.02	0.123	-0.01
30%	0.089	-0.02	0.124	-0.01
40%	0.084	-0.02	0.138	0.01
60%	0.072	-0.03	0.134	0.00
75%	0.070	-0.03	0.154	0.02

(a) Mortar bars made and tested in general accordance with ASTM C 157 and C 311.

(b) ASTM C 311 mixtures with pozzolan or slag by mass; all other mixtures are by solid volume.

Table 14

Drying-Shrinkage Data for High-Alkali Cement RC-715 with Different Amounts of Pozzolan or Slag at 28 and 180-Day Ages[(a)]

	Drying-Shrinkage (%) At			
	28 Days		180 Days	
	Within a Mixture	Between Test and Control Mixtures	Within a Mixture	Between Test and Control Mixtures
RC-715	S_c 0.109		S_c 0.111	
	S_t	$S_t - S_c$	S_t	$S_t - S_c$
With Fly Ash AD-784				
20%[(b)]	0.114	0.00	0.120	0.01
30%	0.092	-0.02	0.110	0.00
35%	0.089	-0.02	0.112	0.00
40%	0.083	-0.03	0.108	0.00
60%	0.062	-0.05	0.090	-0.02
65%	0.052	-0.06	0.083	-0.03
With Silica Fume AD-536(5)				
5%	0.079	-0.03	0.102	-0.01
10%	0.096	-0.01	0.120	0.01
15%	0.119	0.01	0.149	0.04
20%[(b)]	0.179	0.07	0.210	0.10
With Silica Fume AD-797				
5%	0.108	0.00	0.112	0.00
10%	0.128	0.02	0.135	0.02
15%	0.142	0.03	0.158	0.05
20%[(b)]	0.182	0.07	0.214	0.10
With Slag AD-798				
20%[(b)]	0.111	0.00	0.120	0.01
30%	0.101	-0.01	0.141	0.03
35%	0.084	-0.02	0.130	0.02
40%	0.094	-0.02	0.136	0.02
60%	0.093	-0.02	0.150	0.04
70%	0.102	-0.01	0.182	0.07

(a) Mortar bars made and tested in general accordance with ASTM C 157 and C 311.

(b) ASTM C 311 mixtures with pozzolan or slag by mass; all other mixtures were by solid volume.

Table 15

Expansion Data for Concrete Mixtures With and Without 75% Slag AD-798

Test	Age, Days	Slag Test Mixture CL-57 CON (RA)[(a)]	Control Mixture CL-57 CON(R)[(a)]	Control Mixture CL-57 CON(3)[(b)]
		Average Expansion, %		
Moist Storage, Normal Temperature	14	0.01	0.01	
	28	0.01	0.01	
	56	0.01	0.01	
	90	0.01	0.01	
	180	0.01	0.01	
	365	0.02	0.02	
ASR	14	0.02	0.00	0.00
	28	0.03	0.01	0.01
	56	0.03	0.01	0.02
	90	0.03	0.01	0.04
	180	0.03	0.01	0.07
	365	0.03	0.02	(e)
		(c)	(d)	
Sulfate Resistance	14	0.00	0.01	
	28	0.01	0.01	
	56	0.01	0.02	
	90	0.01	0.02	
	180	0.01	0.04	
	270	0.01	0.06	
	365	0.02	0.14	

(a) Both mixtures cast September 1985 with RC-756(3).

(b) Cast November 1986; includes 3% reactive opal for sand.

(c) Test started at 12 days age.

(d) Test started at 2 days age.

(e) Not available when report was prepared.

Table 16

Compressive Strength Data for Concrete Test Mixture With 75% Slag AD-798 and a Control Mixture[a]

Age, Days	Slag Test Mixture CL-57 CON (RA)	Control Mixture CL-57 CON (R)
	Average Compressive Strength, MPa (psi)	
2	5.3 (770)	22.0 (3,190)
4	13.3 (1,930)	--[b]
7	17.2 (2,500)	26.1 (3,780)
9	17.9 (2,600)	--[b]
10	19.0 (2,750)	--[b]
12	20.1 (2,910)	--[b]
28	28.3 (4,110)	30.8 (4,460)
90	28.5 (4,130)	34.8 (5,040)
180	28.6 (4,150)	28.3 (4,110)
365	33.0 (4,780)	34.8 (5,040)

(a) Both mixtures cast September 1985 with RC-756(3).

(b) Not determined. The early age testing of both mixtures done to determine starting point (~ 3000 psi) for ASTM C 1012 type test.

Table 17

Expansion Data for Two Concrete Test Mixtures With Silica Fume and a Control Mixture[a]

Test	Age, Days	Test Mixture With 10% Silica Fume AD-536(5) CL-57 CON(10)	Test Mixture With 15% Silica Fume AD-797 CL-57 CON(15)	Control Mixture CL-57 CON(0)
		Average Expansion, %		
Moist Storage, Normal Temperature	14	0.00	0.00	0.00
	28	0.00	0.00	0.00
	56	0.00	0.00	0.00
	90	0.01	0.00	0.00
	180	0.01	0.01	0.01
	365	0.01	0.01	0.01
ASR	14	0.00	0.00	0.00
	28	0.00	0.00	0.01
	56	0.00	0.00	0.01
	90	0.00	0.00	0.01
	180	0.01	0.00	0.01
	365	0.01	0.01	0.02
Sulfate Resistance	14	0.00[b]	0.00[b]	0.00[b]
	28	0.01	0.01	0.00
	56	0.01	0.01	0.00
	90	0.01	0.01	0.01
	180	0.01	0.01	0.02
	270	0.01	0.01	0.02
	365	0.02	0.02	0.05

(a) All three mixtures cast March 1986 with RC-756(3).

(b) Test started at 2 days age.

Table 18

Compressive Strength Data for Two Concrete Test Mixtures With Silica Fume and a Control Mixture[(a)]

Age, Days	Test Mixture With 10% Silica Fume AD-536(5) CL-57 CON(10)		Test Mixture With 15% Silica Fume AD-797 CL-57 CON(15)		Control Mixture CL-57 CON(0)	
	Average Compressive Strength MPa (psi)[(b)]					
1	11.0	(1,600)	17.1	(2,480)	13.5	(1,960)
2	23.2	(3,360)	20.6	(2,980)	19.6	(2,840)
7	26.8	(3,880)	34.2	(4,960)	33.3	(4,830)
28	45.2	(6,560)	45.4	(6,580)	32.1	(4,650)
90	50.6	(7,340)	49.1	(7,120)	34.8	(5,050)
180	50.6	(7,340)	47.6	(6,900)	35.6	(5,170)
365	50.7	(7,360)	47.7	(6,920)	36.2	(5,250)

(a) All 3 mixtures cast March 1986 with RC-756(3).

(b) Early age testing done to determine starting point (~ 3000 psi) for ASTM C 1012 type test.

Table 19

Expansion Data for Two Concrete Test Mixtures With Fly Ash AD-784 or Slag AD-856 and a Control Mixture[(a)]

Test	Age, Days	Test Mixture With 60% Fly Ash CL-57CON(60A)[(b)]	Test Mixture With 60% Slag AD-856 CL-57 CON(60S)	Control Mixture CL-57 CON(02)
		Average Expansion, %		
Moist Storage, Normal Temperature	14	0.00	0.00	0.00
	28	0.01	0.00	0.00
	56	(c)	0.00	0.00
	90	0.01	0.01	0.00
	180	0.01	0.01	0.00
	365	0.02	0.01	0.01
ASR	14	0.00	0.00	0.00
	28	0.01	0.01	0.01
	56	(c)	0.01	0.01
	90	0.02	0.01	0.01
	180	0.02	0.01	0.01
	365	0.03	0.02	0.02
		(d)	(e)	(d)
Sulfate Resistance	14	0.00	0.00	0.00
	28	0.00	0.01	0.00
	56	(c)	0.01	0.00
	90	0.01	0.01	0.01
	180	0.02	0.01	0.01
	270	0.02	0.01	0.02
	365	0.03	0.01	0.02

(a) All 3 mixtures cast May 1986 with RC-756(3).

(b) The mixture with fly ash had 1% of the sand replaced by CH to accelerate strength gain.

(c) Not read.

(d) Test started at 2 days age.

(e) Test started at 5 days age.

Table 20

Compressive Strength Data for Two Concrete Test Mixtures With Fly Ash AD-784 or Slag AD-856 and a Control Mixture[(a)]

Age, Days	Test Mixture With 60% Fly Ash AD-784 CL-57 CON(60A)		Test Mixture With 60% Slag AD-856 CL-57 CON(60S)		Control Mixture CL-57 CON(02)	
	Average Compressive Strength, MPa (psi)					
1	6.2	(900)	(b)		14.5	(2,100)
2	~20.7	(3,000)	7.4	(1,070)	20.7	(3,000)
7	44.6	(6,470)	26.3	(3,820)	31.6	(4,580)
28	53.8	(7,800)	38.4	(5,570)	37.7	(5,470)
90	56.7	(8,230)	42.4	(6,150)	36.8	(5,330)
180	58.5	(8,490)	41.0	(5,950)	38.4	(5,570)
365	65.0	(9,430)	44.5	(6,450)	40.5	(5,880)

(a) All 3 mixtures cast May 1986 with cement RC-756(3).

(b) Not determined; early age data testing of all mixtures done to determine starting point (~ 3000 psi) for ASTM C 1012 test.

Table 21

Sulfate Resistance Expansion Data for 3 Rounds of a Concrete Control Mixture[a]

Age, Days	Mixture CL-57 CON (R)	Mixture CL-57 CON (O)	Mixture CL-57 CON (O2)	3 Round Average
		Average Expansion, %		
14	0.01	0.00	0.00	0.00
28	0.01	0.00	0.00	0.00
56	0.02	0.00	0.00	0.00
90	0.02	0.01	0.01	0.01
180	0.04	0.02	0.01	0.02
270	0.06	0.02	0.02	0.03
365	0.14	0.05	0.02	0.07

(a) Data repeated from Tables 15, 17, and 19.

Table 22

Compressive Strength Data for Several Rounds of a Concrete Control Mixture[(a)]

Age, Days	CL-57 CON (R)		CL-57 CON (0)		CL-57 CON (02)		3 Round Average		CL-57 CON (3)[(b)]	
	Average Compressive Strength, MPa (psi)									
1			13.5	(1,960)	14.5	(2,100)	13.8	(2,000)	14.4	(2,090)
2	22.0	(3,190)	19.6	(2,840)	20.7	(3,000)	20.8	(3,010)		
7	26.1	(3,780)	33.3	(4,830)	31.6	(4,580)	30.3	(4,400)	26.8	(3,880)
28	30.8	(4,460)	32.1	(4,650)	37.7	(5,470)	33.5	(4,860)	28.1	(4,070)
90	34.8	(5,040)	34.8	(5,050)	36.8	(5,330)	35.4	(5,140)	29.0	(4,210)
180	28.3	(4,110)	35.6	(5,170)	38.4	(5,570)	34.1	(4,950)	32.5	(4,710)
365	34.8	(5,040)	36.2	(5,250)	40.5	(5,880)	37.2	(5,390)	(c)	

(a) Data for mixtures CL-57 CON(R), (O), and (02) from Tables 16, 18, and 20.

(b) This mixture cast Nov 1986 with 3 percent of sand replaced with reactive opal to cause ASR.

(c) Not available when report was prepared.

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